Considerations from Line Intensity Mapping for next generation Filterbank Spectrometers

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Introduction

[CII] Line Intensity Mapping (LIM) surveys

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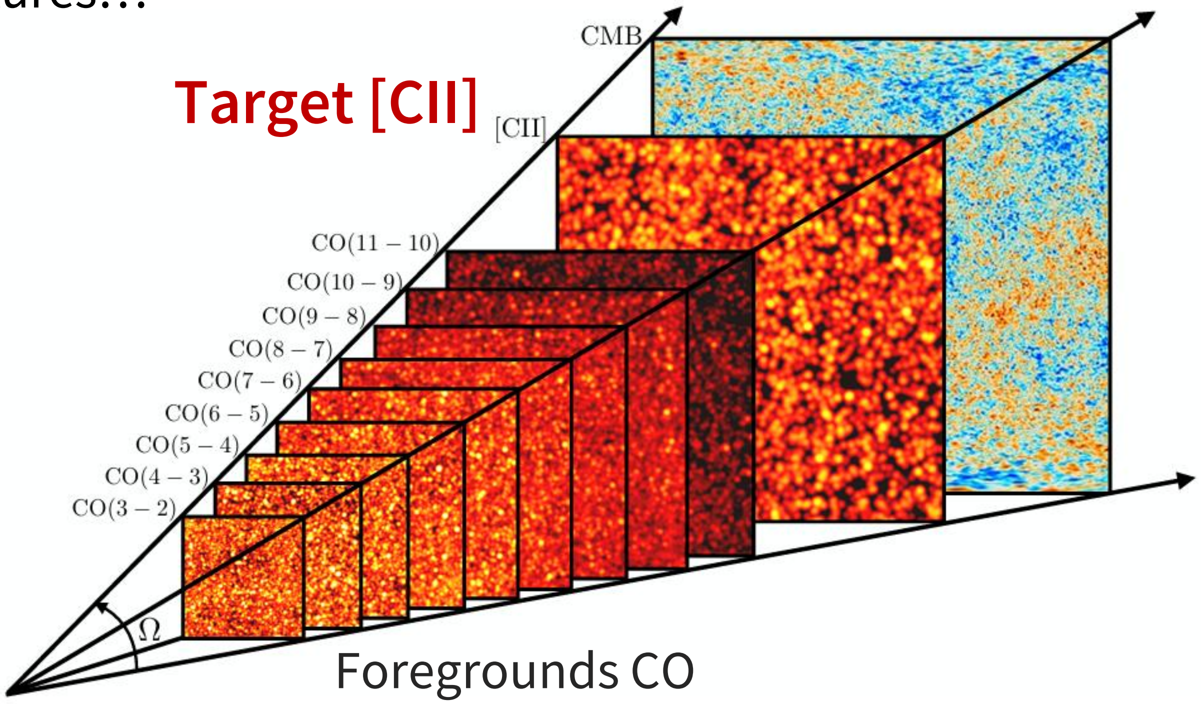
Tracing massive star formation in large scale structures…



A ‘snapshot’ intensity map at $z \sim 3.6$ [Roy+, 25]

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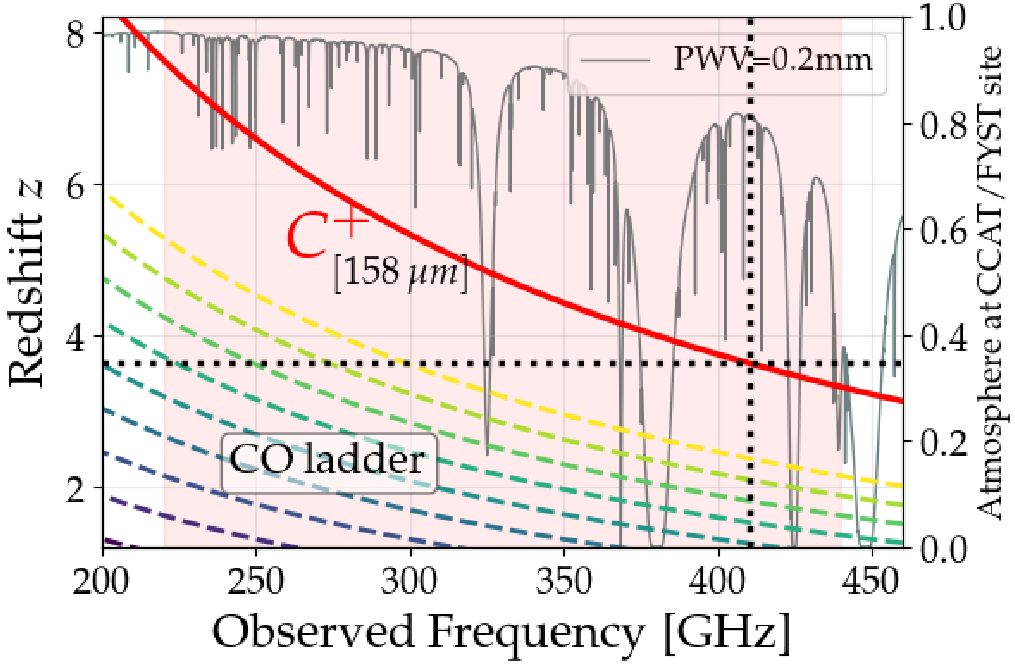
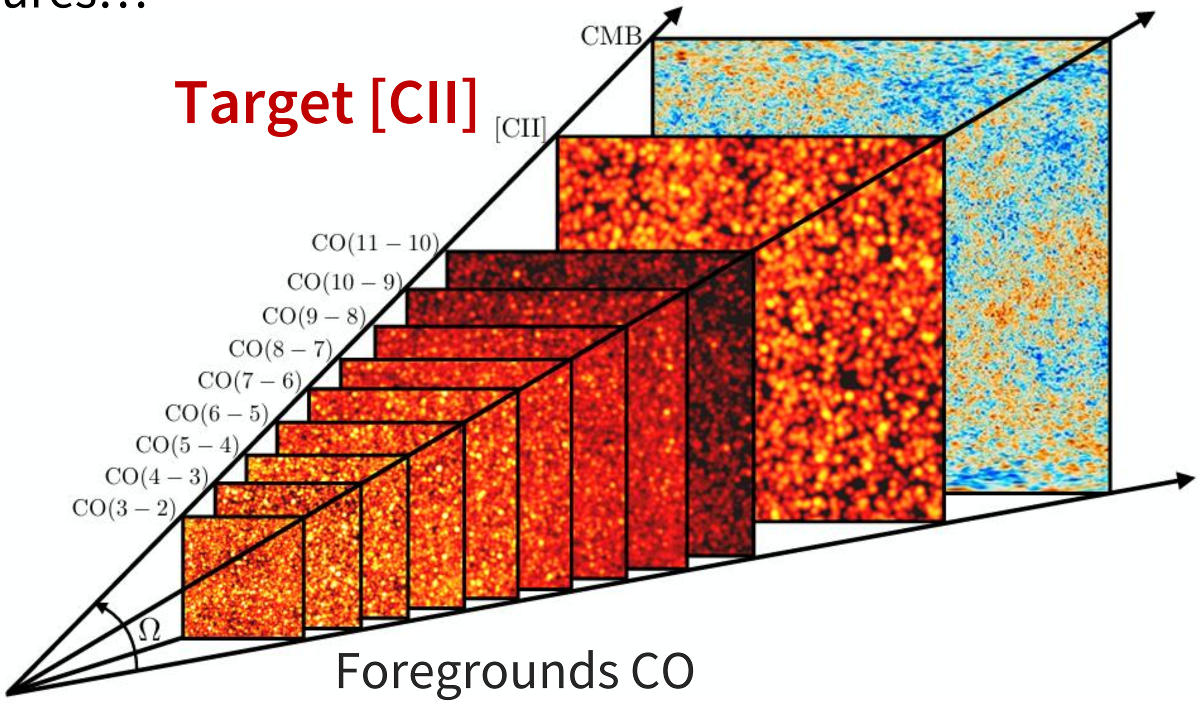
[CII] Line Intensity Mapping (LIM) surveys

Tracing massive star formation in large scale structures…

… across wide redshifts





A ‘snapshot’ intensity map at $z \sim 3.6$ [Roy+, 25]

→ A dedicated spectrometer for LIM surveys?

First generation instrument

EoR-Spec on PrimeCam/FYST

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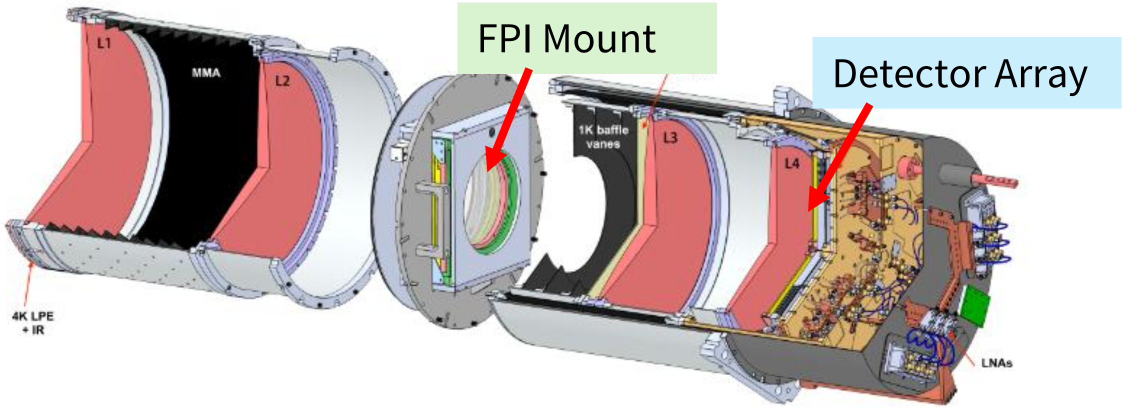
$R \sim 100$ Fabry-Perot Interferometer (FPI) [Nikola+, 23]



FYST Deep Spectroscopic Survey (DSS)

- Two 2° x 2° fields
- Needs ~ 4000 hours integration

- Two spectral bands – **260 GHz** & **370 GHz**

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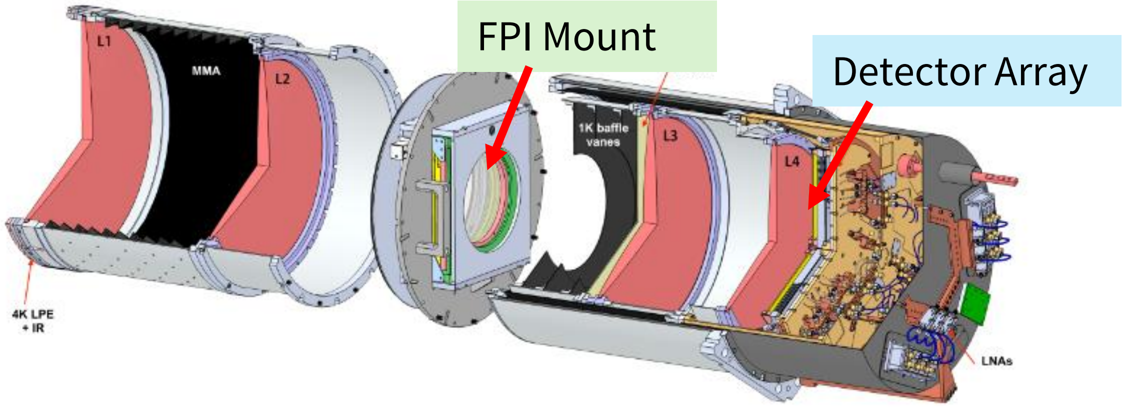

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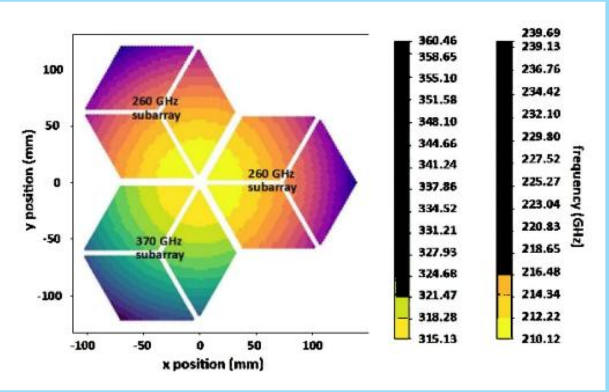
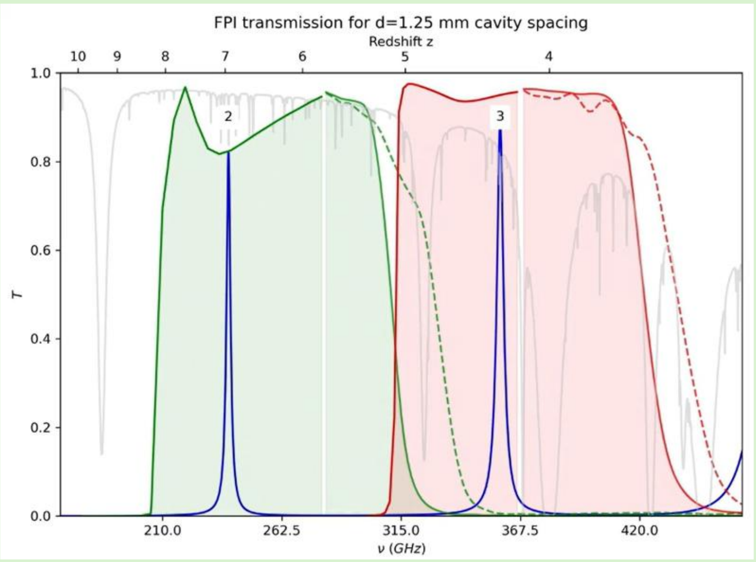


Three focal plane sub-arrays with *Kinetic Inductance Detectors (KIDs)*



Transmission at one FPI step [Freundt+, 26]

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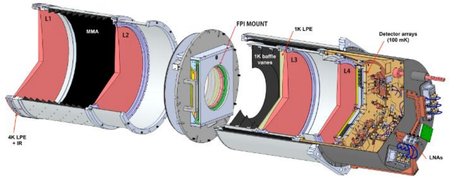
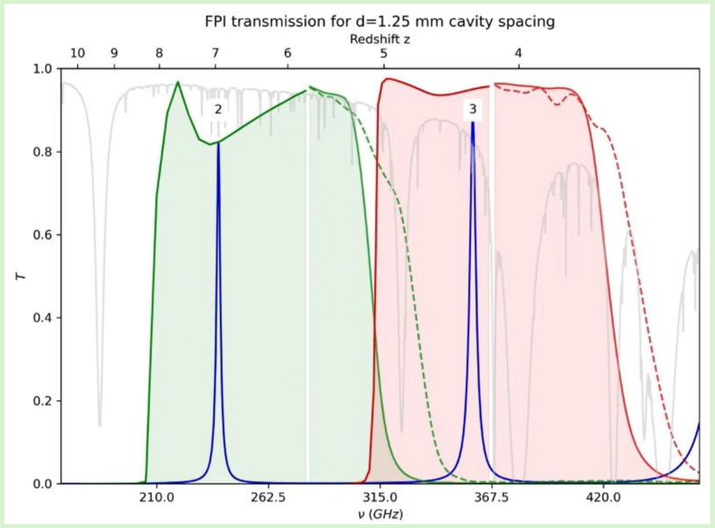


Detector Array

FPI Mount

[Freundt+, 26]



- Multiple FPI scanning steps for full BW coverage
- Limited to a **Lorentzian** profile

Next generation instrument?

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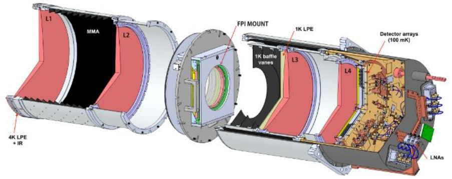
R ~ *100* Fabry-Perot Interferometer [Nikola+, 23]



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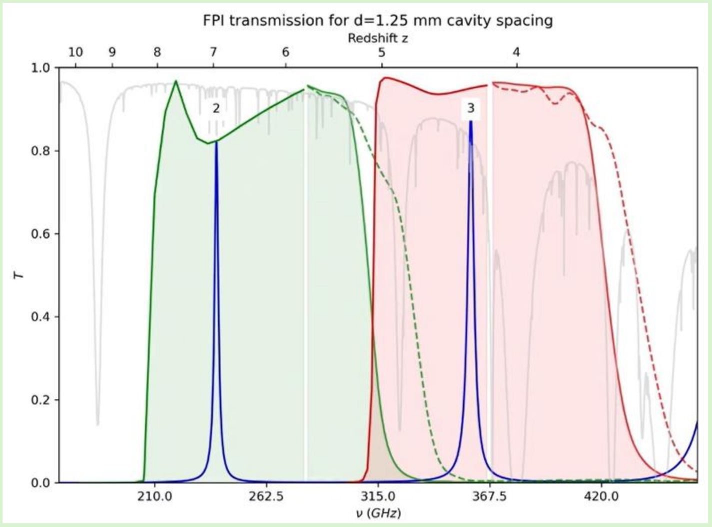

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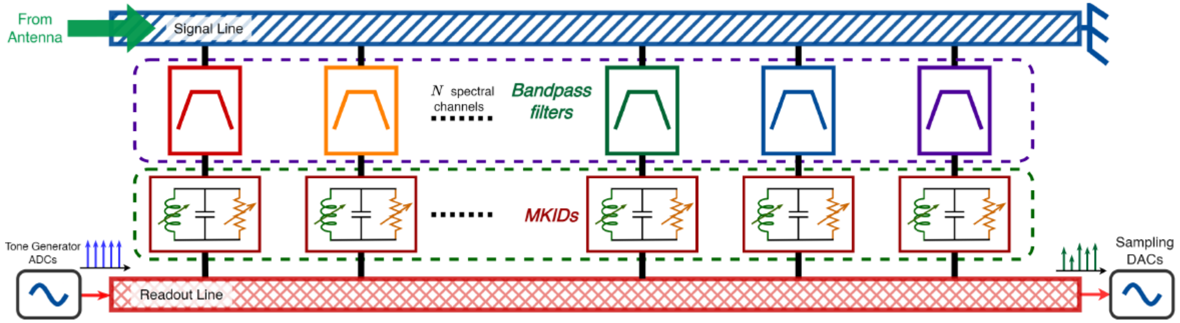
Filterbank Spectrometers



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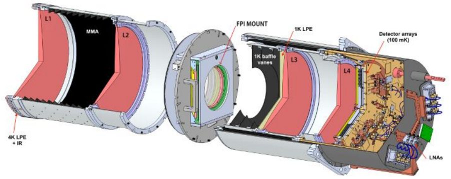

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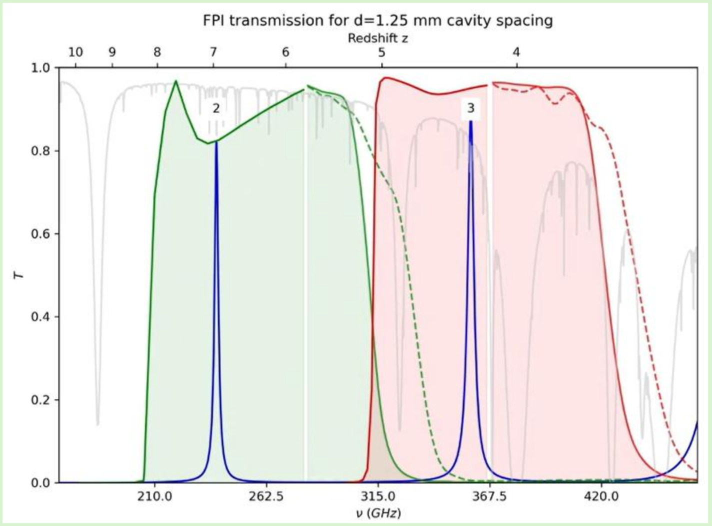

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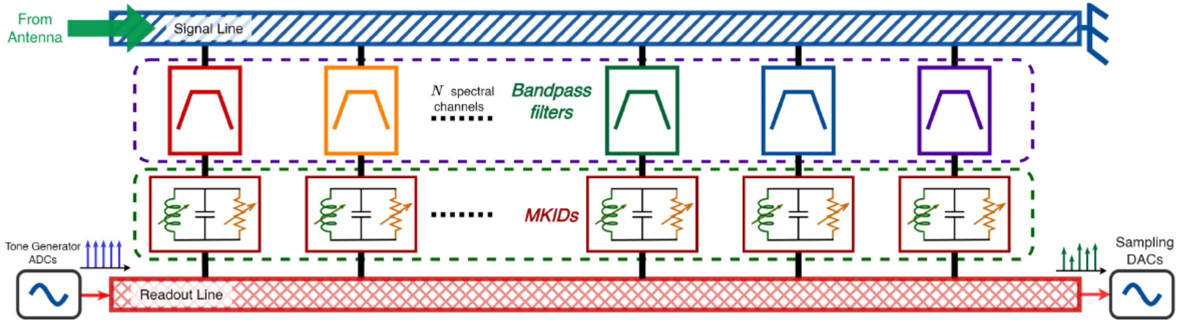
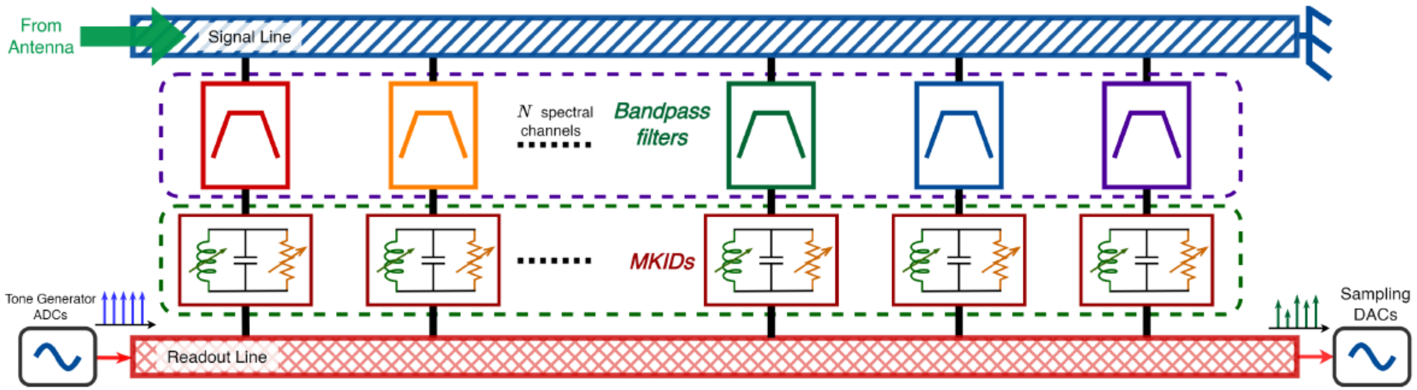


- Compact design for a Focal Plane Array
- Same detector technology (KIDs)
- Advantages:
  - Simultaneous full bandwidth coverage
  - **Arbitrary** spectral profiles possible

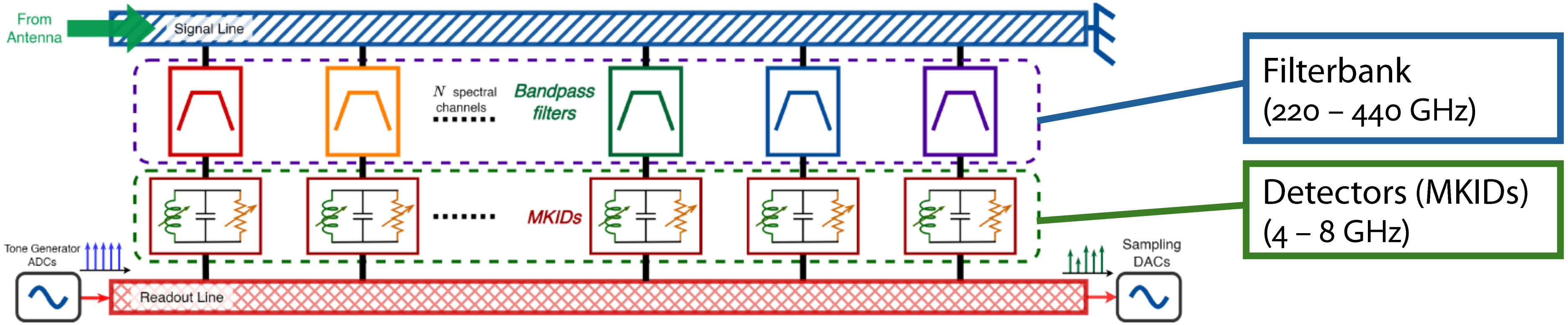
Filterbank Spectrometers



Concept schematic for a Filterbank Spectrometer

Filterbank Spectrometers

- Filterbank section
  - Series of Bandpass filters sets the spectral channels
  - Each channel feeds to a power detector (KIDs)
  - All detectors "observe" simultaneously
- Integrated structure on a single wafer
- Operates at superconducting temperatures (~ 100 mK)



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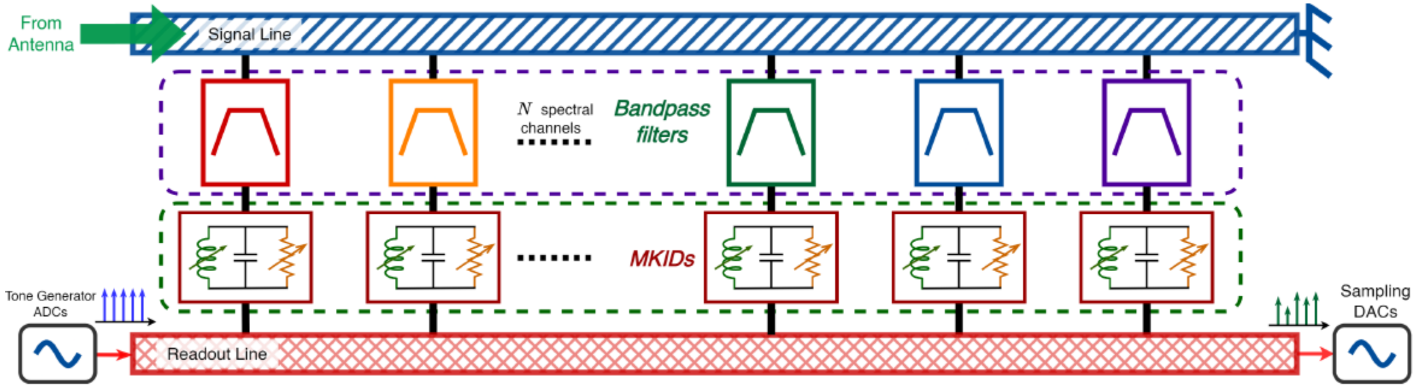
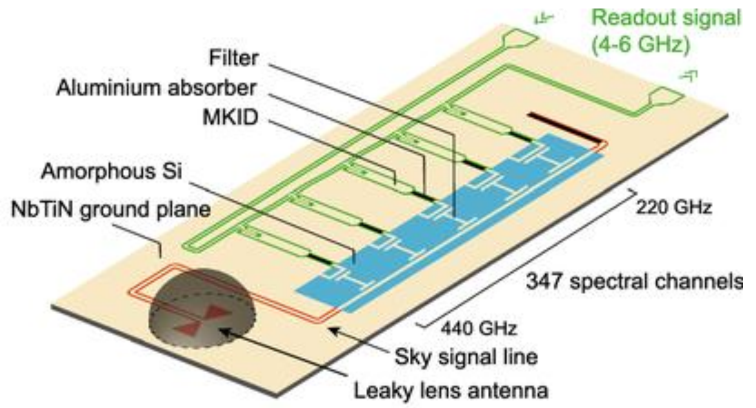
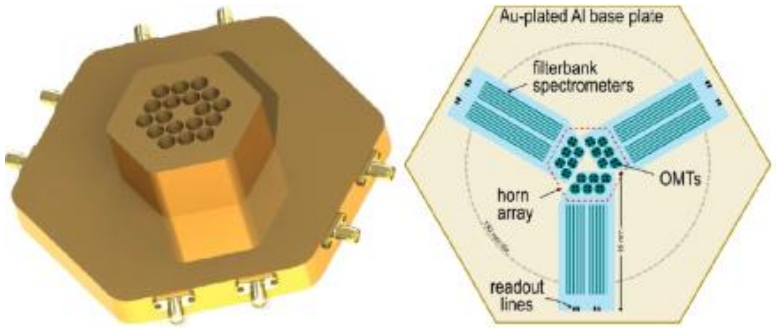


Concept schematic for a Filterbank Spectrometer

Technology demonstration



DESHIMA2 / TIFUUN for ASTE [Endo+, 22]



SLIM for SPT [Karkare+, 24]

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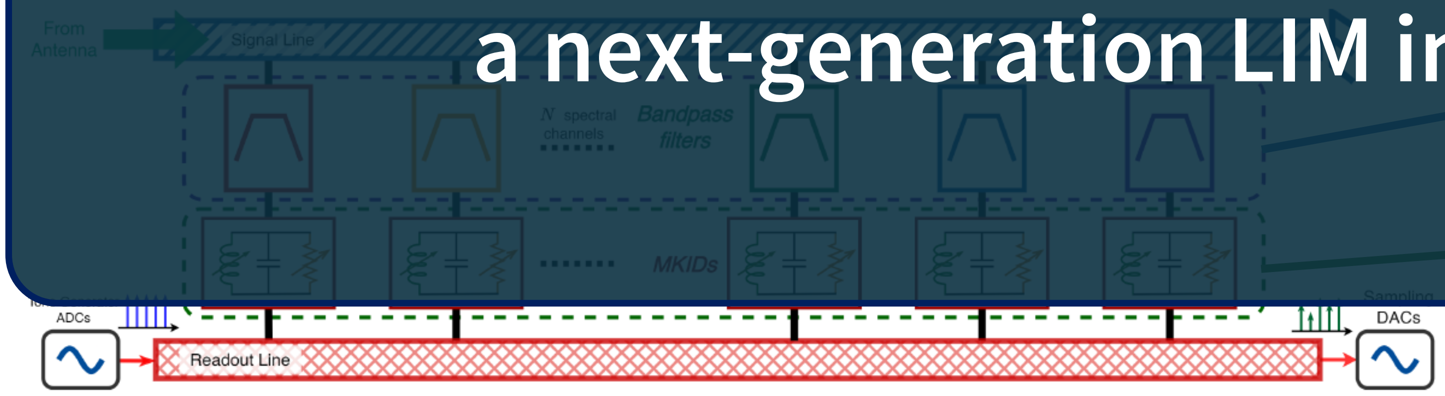
How to adapt this technology for a next-generation LIM instrument?



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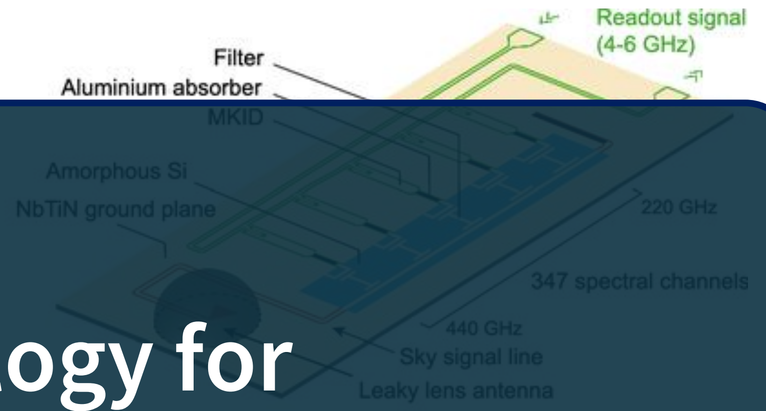


DESHIMA2 / TIFUUN for ASTE [Endo+, 22]

Filterbank (220 – 440 GHz)

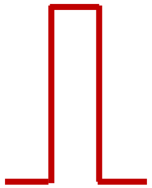
Detectors (MKIDs) (4 – 8 GHz)

SLIM for SPT [Karkare+, 24]

Considerations

What spectrometer profile is suitable?

- Can we realise different spectral profiles?



Ideal “boxcar” shape? ☹

What is the expected Spectrometer performance?

Can we develop this Spectrometer in-house?

Spectrometer Profiles

Parameterise the spectral transmission $T(f)$ –

- Channel frequency, f_0
- Resolution R ($= Q_L = f_0/\Delta f$)
- Spectral order N

Butterworth profile

$$T(f) = \frac{T_{max}}{1 + \left[2\,Q_L\left(\frac{f - f_0}{f_0}\right)\right]^{2N}}$$

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Translate to a design → *a "single-channel"* implementation

- A planar filter structure that gives desired $T(f)$
- With superconducting metallisation (T ~ 200 mK)

Spectrometer Profiles – a design study

EM Realisation with single channel designs

@ $f_0 = 275$ GHz, R (= Q_L) ~ 100

Butterworth profile

$$T(f) = \frac{T_{max}}{1 + \left[2\,Q_L\left(\frac{f - f_0}{f_0}\right)\right]^{2N}}$$

(a)

(b)

(c)

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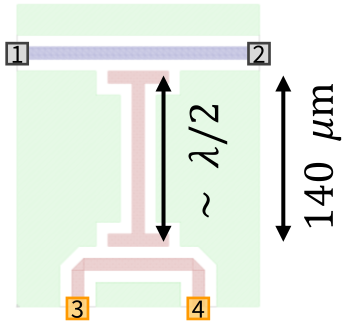


Halfwave Resonator

[Laguna+, 21; Robson+, 22]

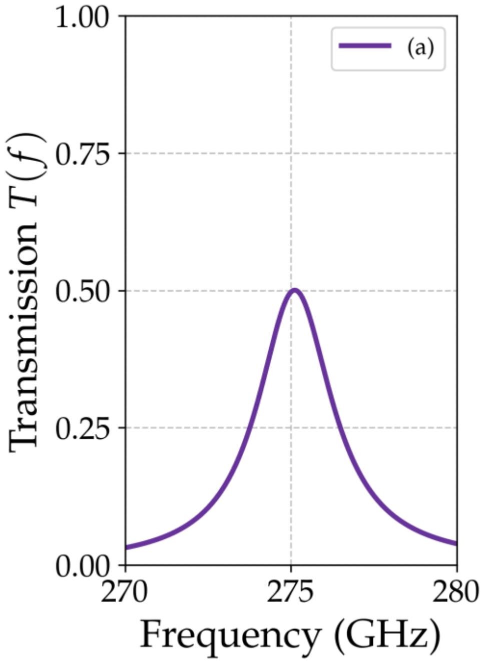
$T_{max} = 0.5$

$N = 1$

- Fundamentally limited to 50%
- Lorentzian profile

(b)

(c)



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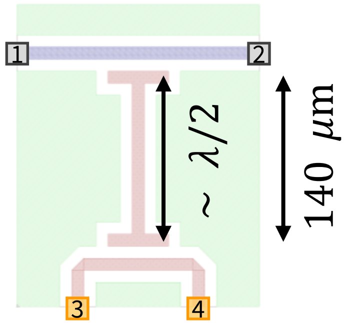

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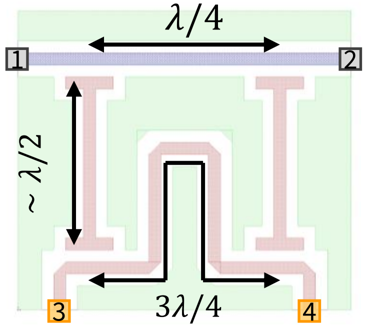
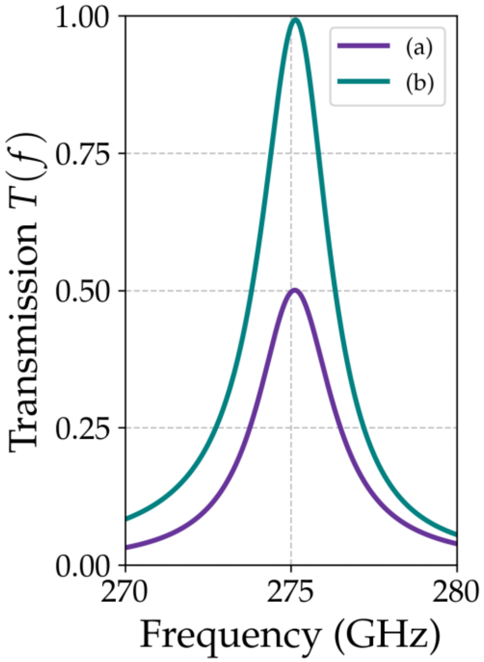


Directional Filter
[Marting+, 24]

$T_{max} = 1$
$N = 1$

- Phase-coherent structure to get 100%
- Still Lorentzian!

(c)



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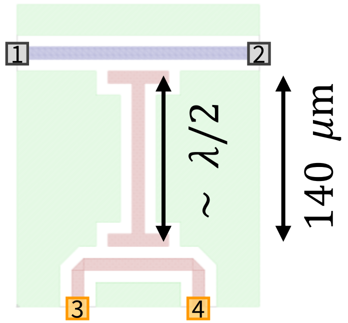

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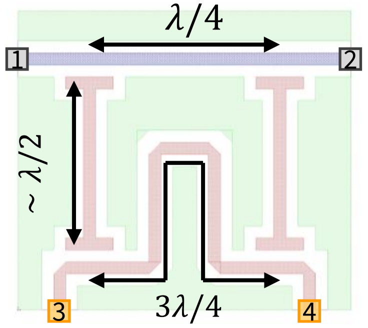

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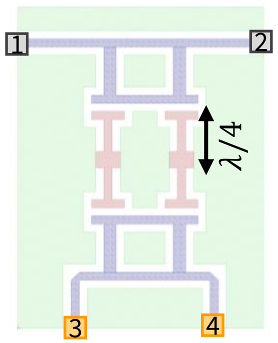
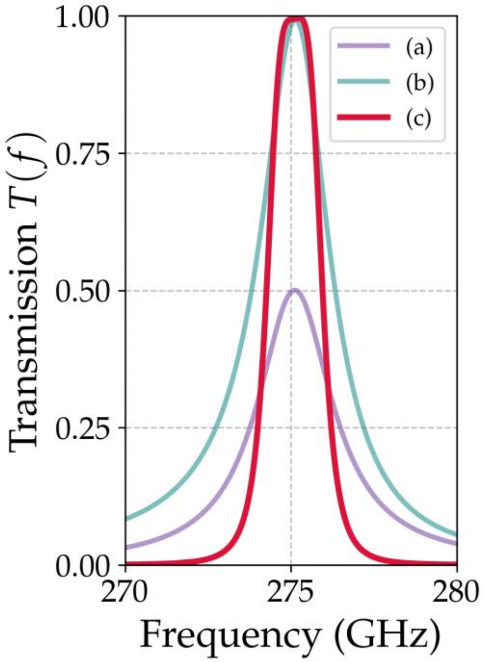


Cross Filter
Novel implementation [Saha+, 26]

$T_{max} = 1$
$N = 2$

- **Improved spectral roll-off with unity transmission!**

→ Closer to "boxcar" shape



Considerations

What should be the Spectrometer profile?

- Can we realise different spectral profiles? ✓
- **Implication on spectrometer efficiency?**

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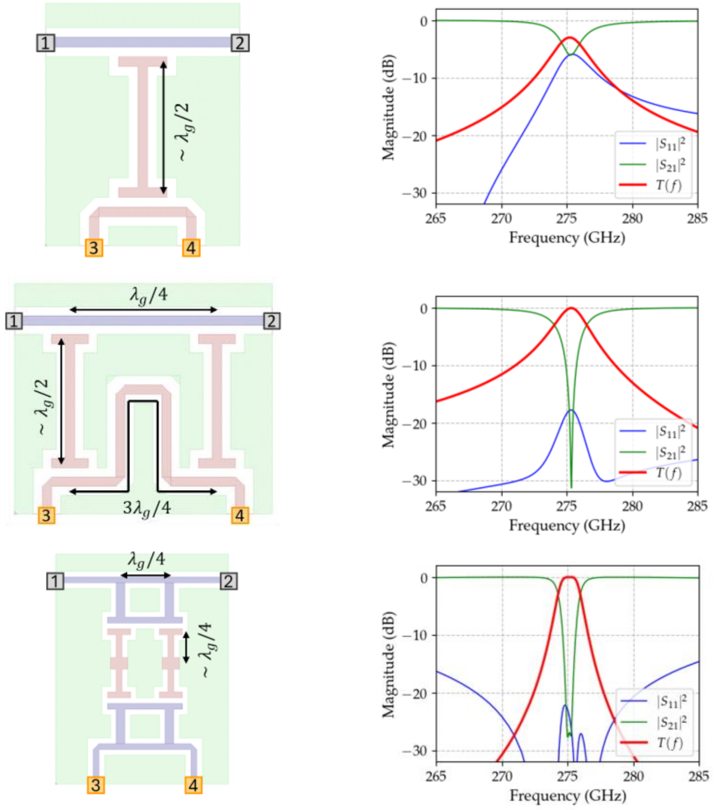
Can we develop this Spectrometer in-house?

Cascading Effects in Filterbank Spectrometers

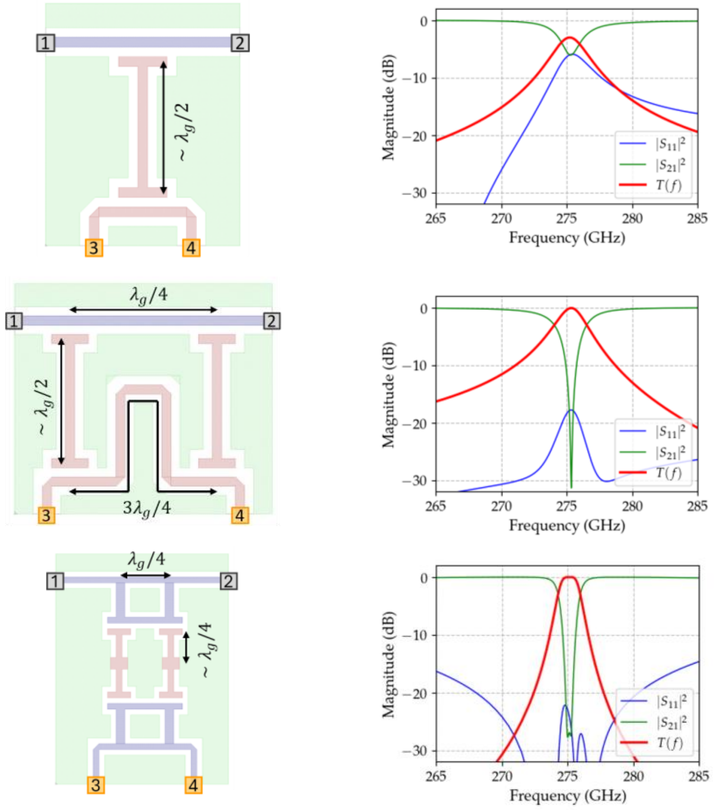
Single Channel



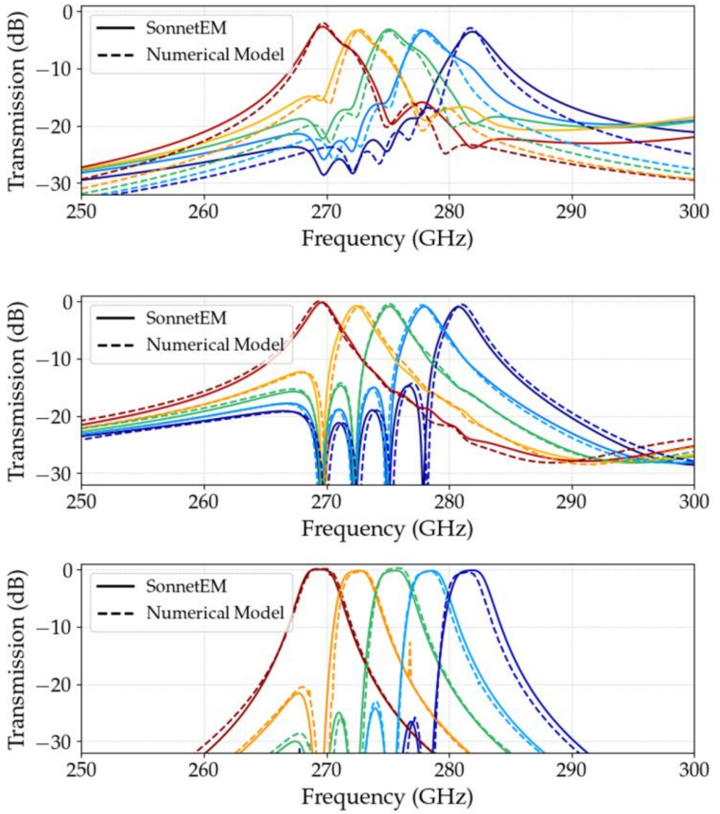
Cascading Effects in Filterbank Spectrometers

- Overlapping adjacent passbands interact and alter the final spectrometer profiles [Saha+, 25]
- Results in **lowered peak** and **increased crosstalk** than single channel profile

Single Channel



$N_c = 5$ small filterbank

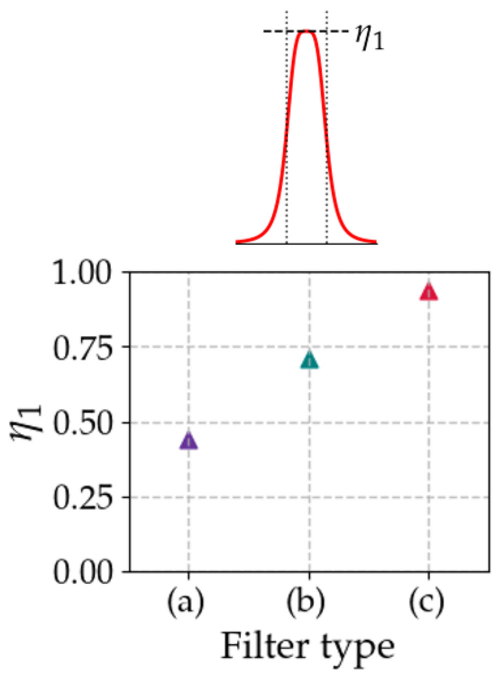


Lower crosstalk results in lesser deterioration

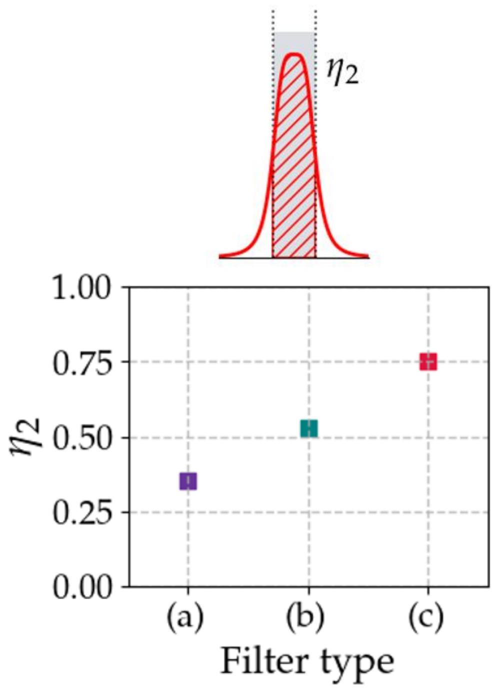
Spectrometer Efficiency

- … thus resulting in lower efficiencies than a single channel [Saha+, 26]

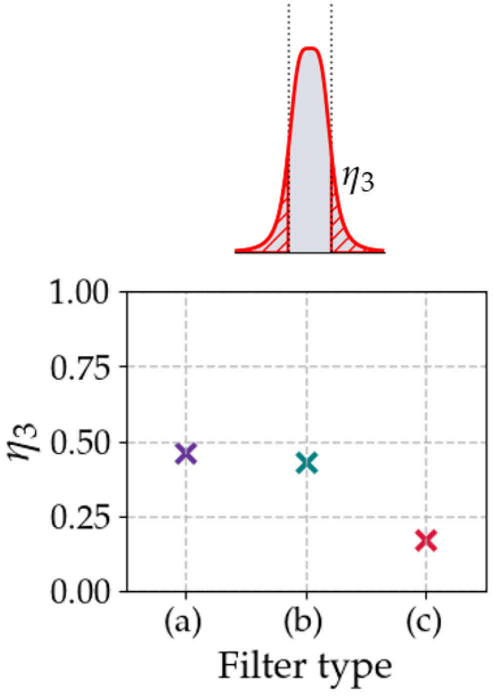
Peak Efficiency



In-band fraction



Crosstalk



Our novel design (c) results in improved spectrometer efficiencies → **better sensitivity!**

Considerations

What should be the Spectrometer profile?

- Can we realise different spectral profiles? ✓
- Implication on spectrometer efficiency?
- **What Resolution?**

What is the expected Spectrometer performance?

Can we develop this Spectrometer in-house?

Spectral Resolution

$R \sim 100$ – based on expected clustering signal at $z \leq 6$ **But what's a suitable R?**

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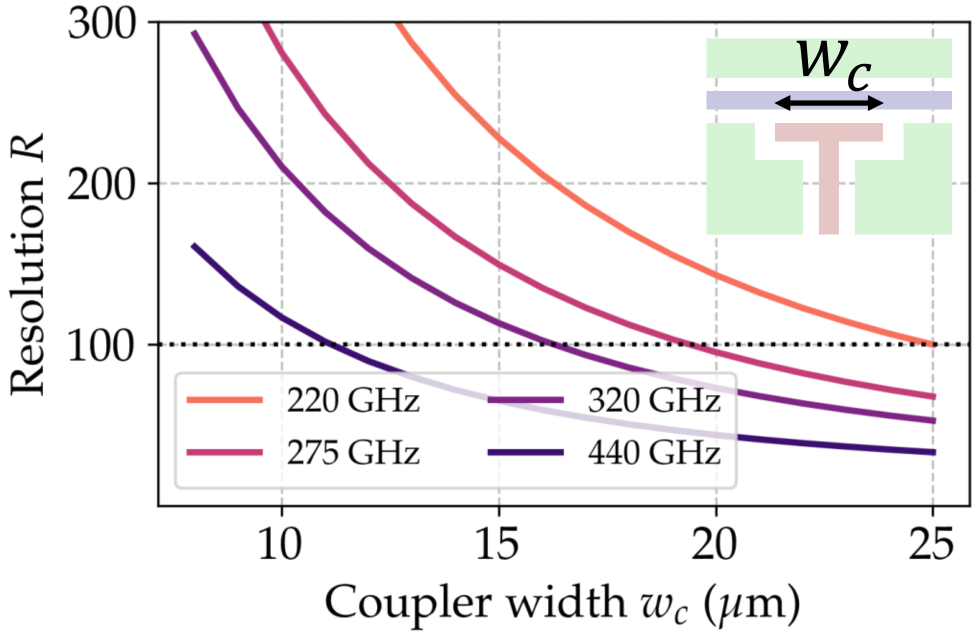

Coplanar Waveguide (CPW) coupling gives $R \sim 50 - 300$ across all channels

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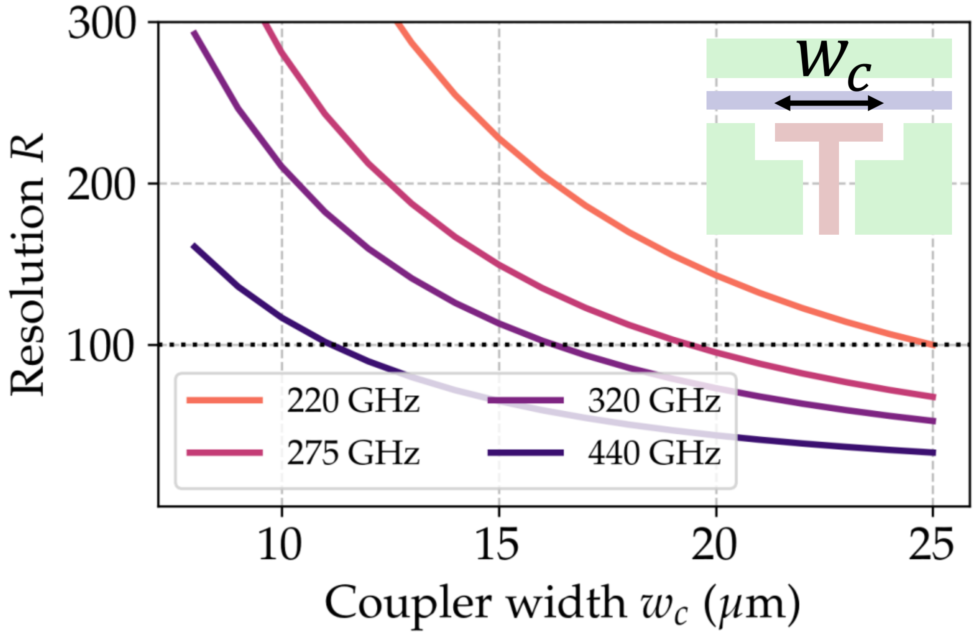
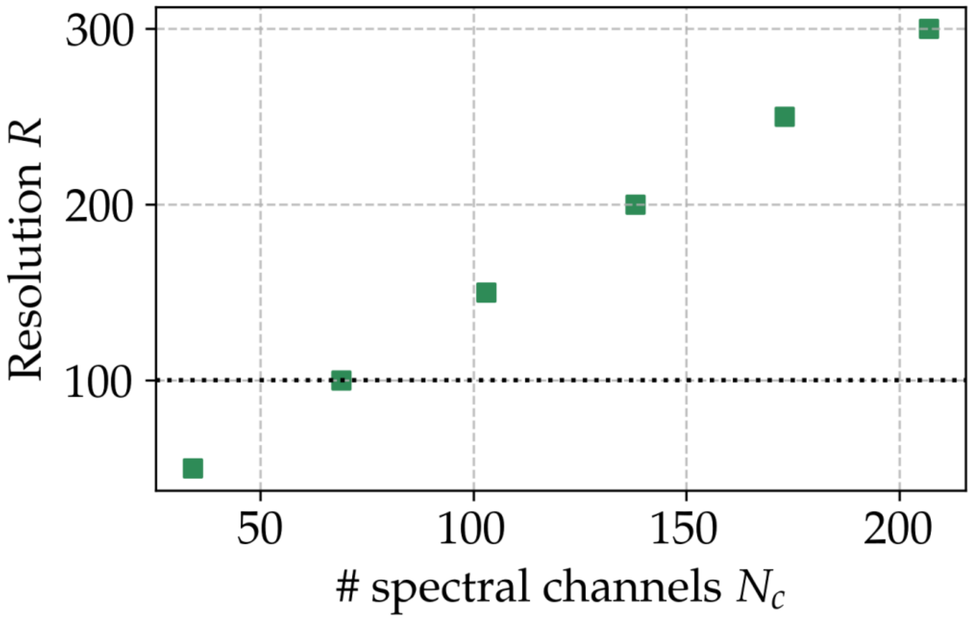


Coplanar Waveguide (CPW) coupling gives $R \sim 50 - 300$ across all channels

But… spectrometer size!



→ **Miniaturisation** becomes necessary!

Considerations

What should be the Spectrometer profile?

- Can we realise different spectral profiles? ✓
- Implication on spectrometer efficiency?
- What Resolution?

What is the expected Spectrometer performance?

- **Influence on the [CII] signal recovery?**

Can we develop this Spectrometer in-house?

Spectral profile and signal recovery

- Spectrometer generates Intensity Cubes

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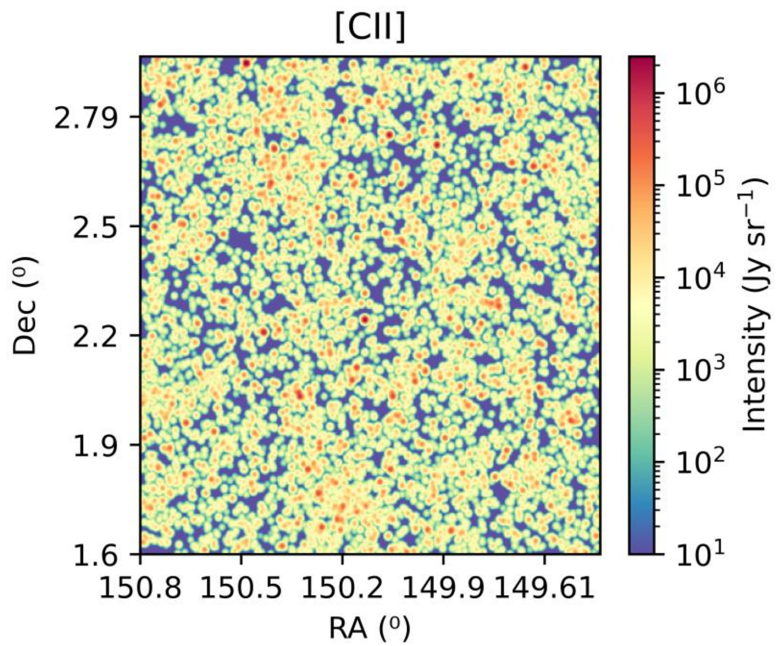
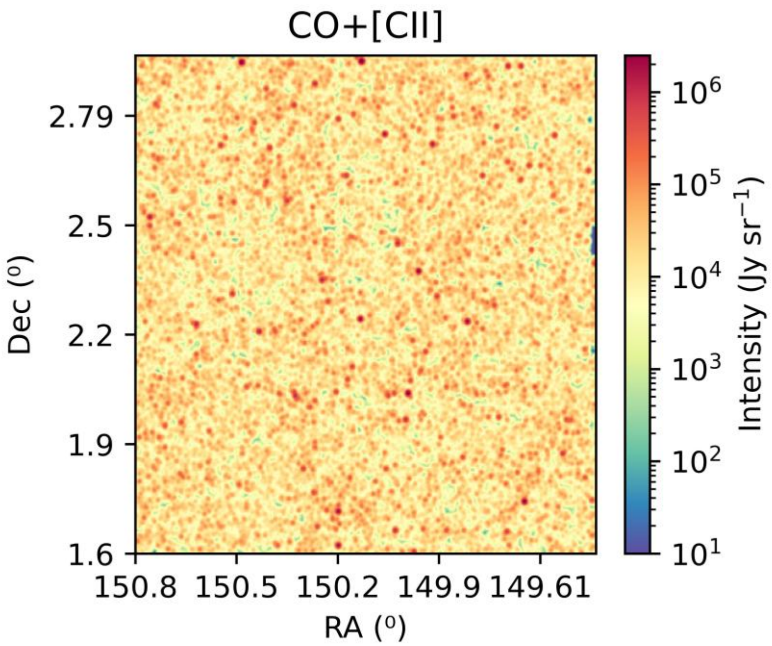


Target [CII] map ~ 350 GHz



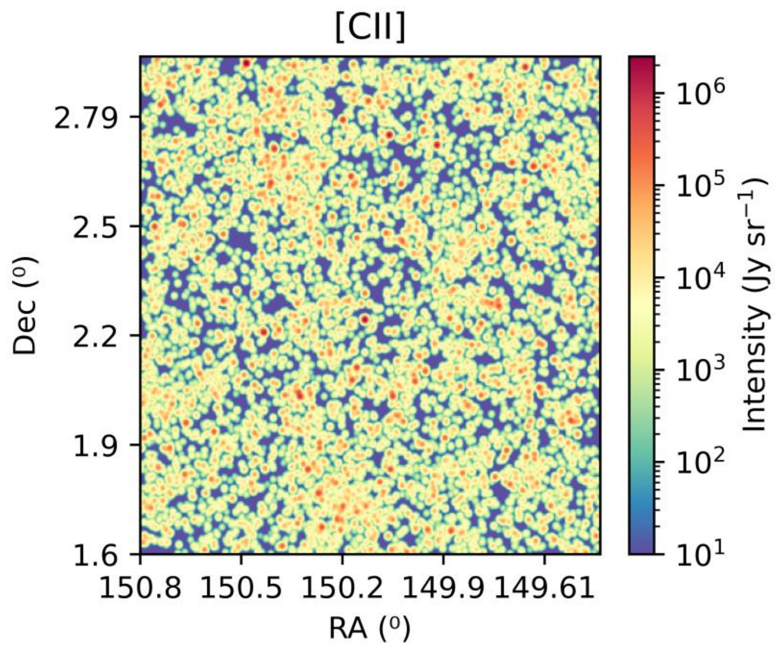
Observed map with CO interlopers

Credits: J. Clarke

Spectral profile and signal recovery

- Spectrometer generates Intensity Cubes → [CII] power spectrum recovery techniques

  → ***See Jonathan Clarke's talk next!***



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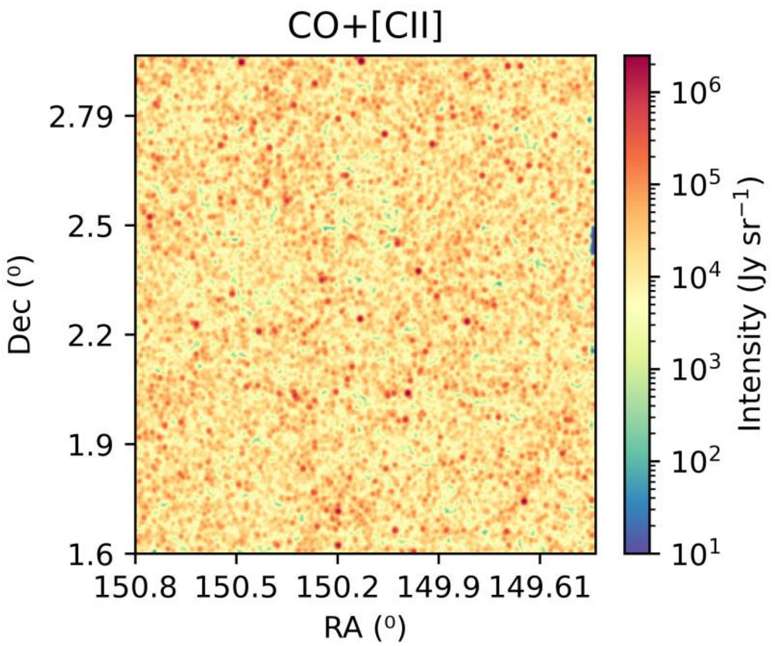

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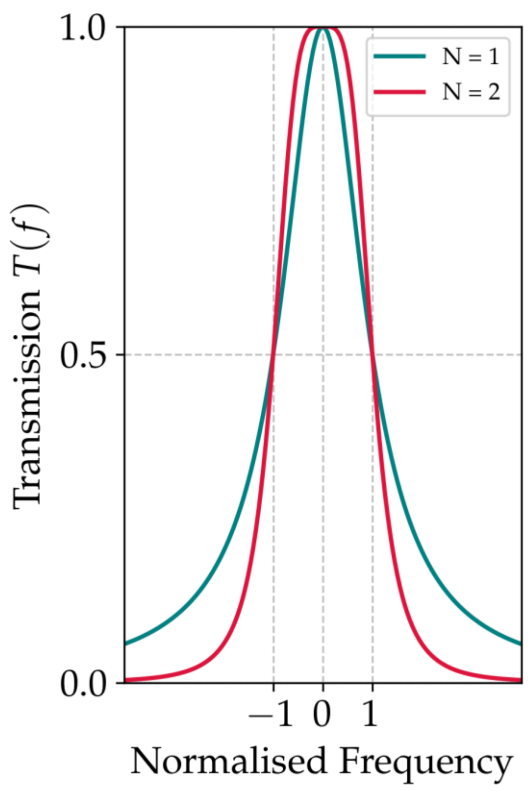
Does the spectral profile helps in foreground removal?



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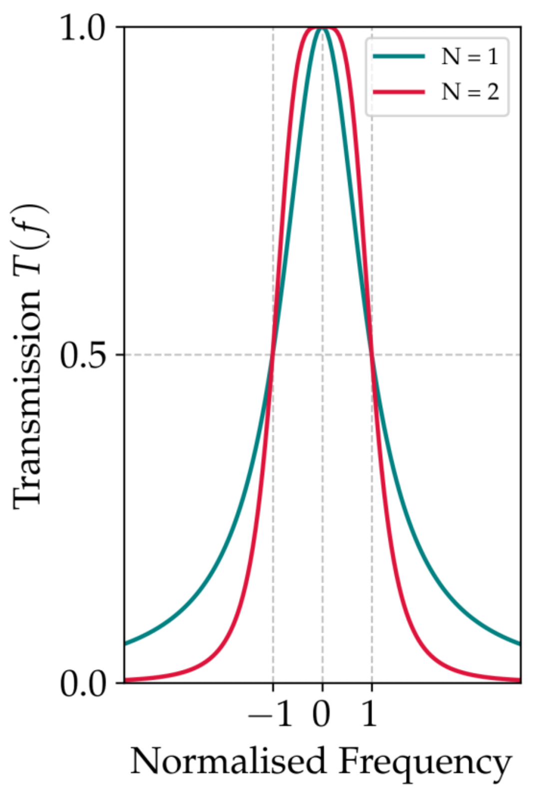
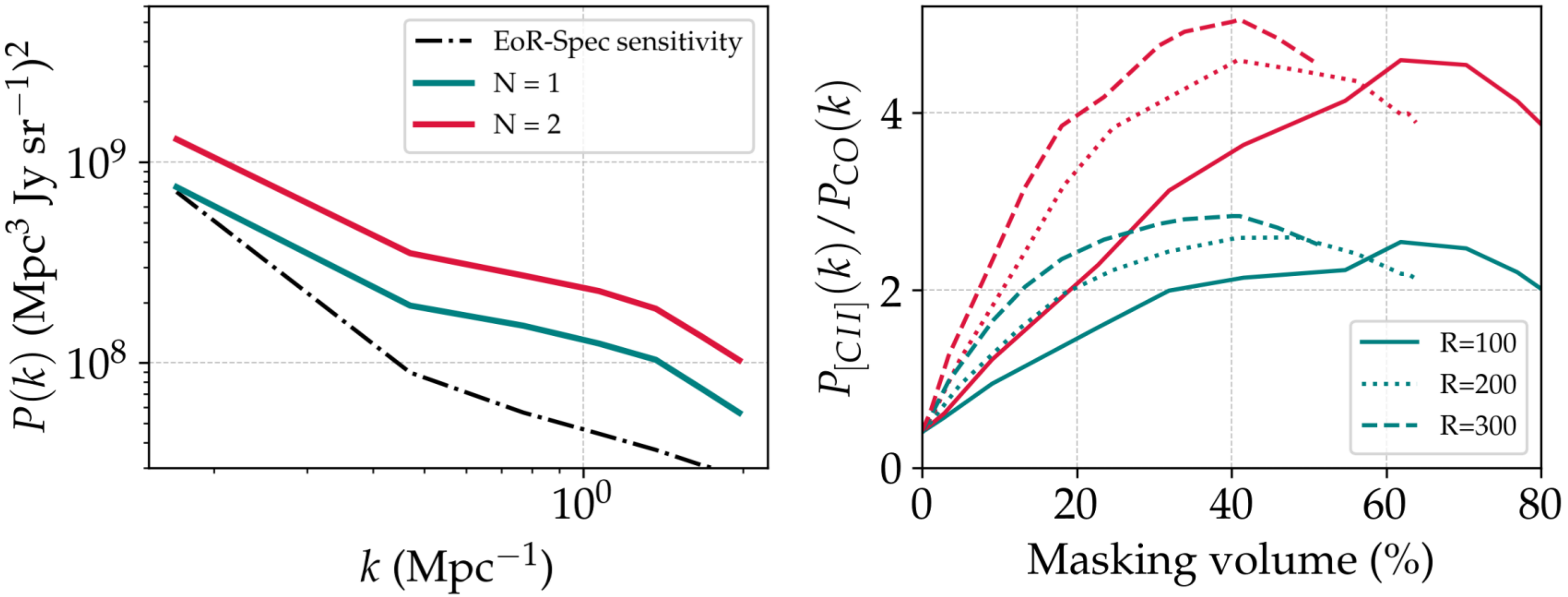


Voxel masking → CO interlopers removal [Clarke+, 26]



Testing masking effectiveness with different spectral profiles

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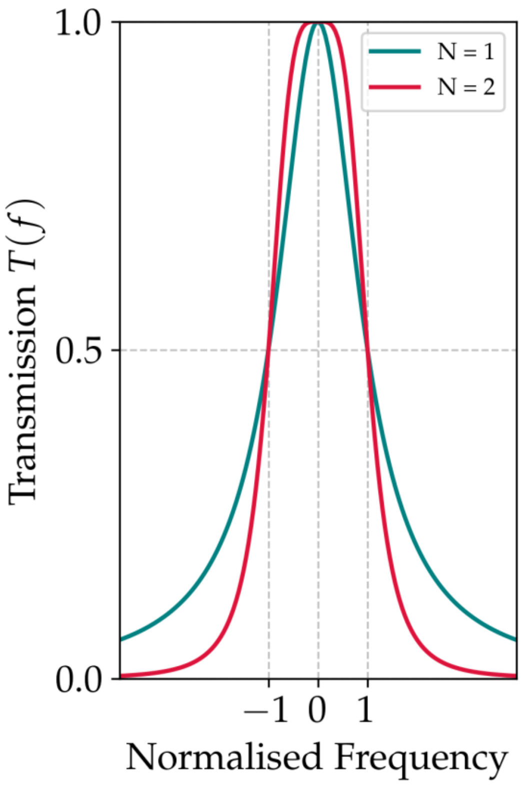
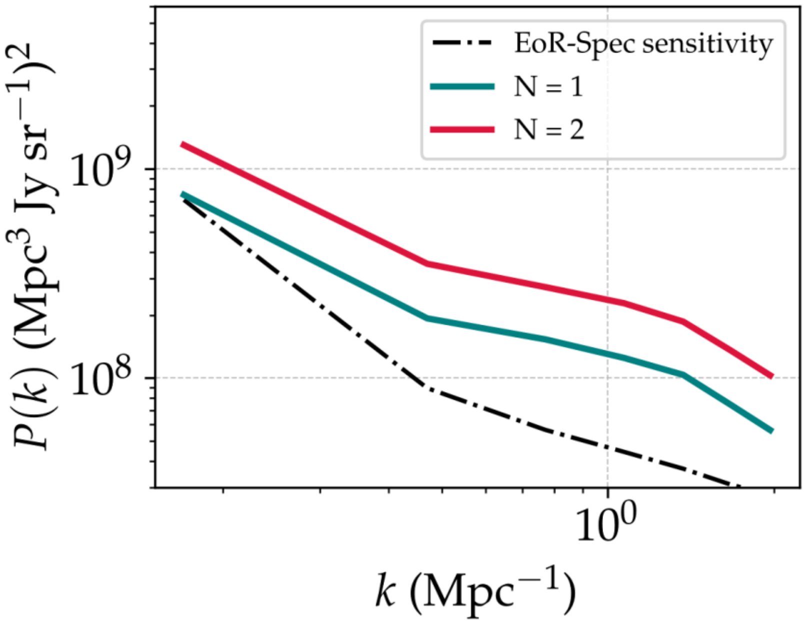
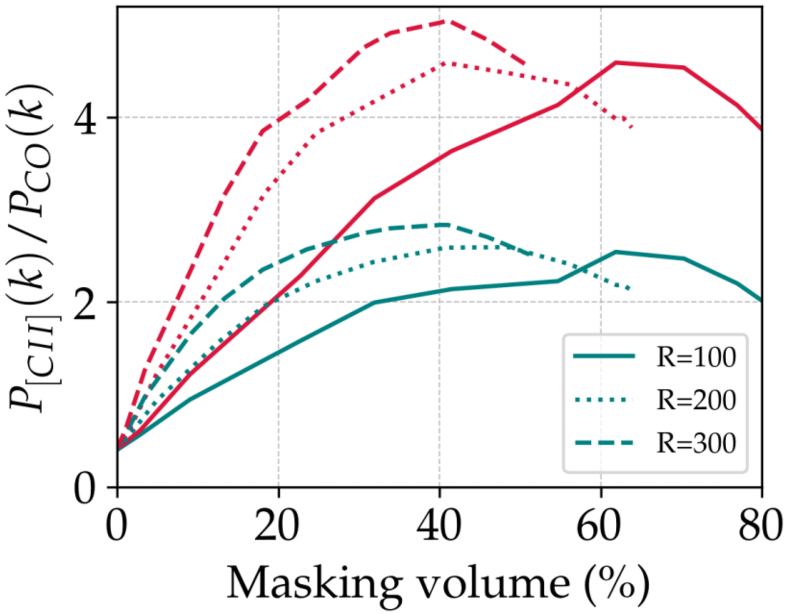


Voxel masking → CO interlopers removal [Clarke+, 26]





Testing masking effectiveness with different spectral profiles

→ *Lower crosstalk makes voxel masking more effective*

Considerations

What should be the Spectrometer profile?

- Can we realise different spectral profiles? ✓
- Implication on spectrometer efficiency?
- What Resolution?

What is the expected Spectrometer performance?

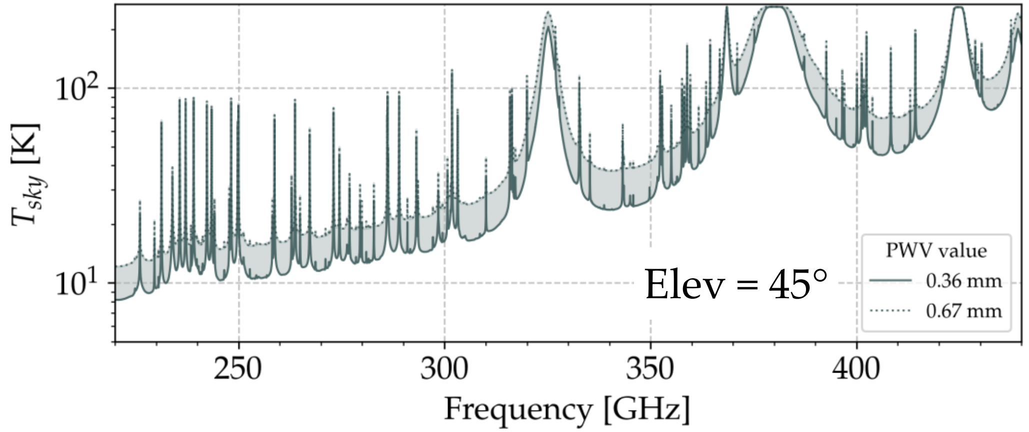
- Influence on the [CII] signal recovery?
- **Specifications on the detector noise?**

Can we develop this Spectrometer in-house?

Detector considerations

Implications on the detector performance?

- Atmosphere dominates the optical loading to the detectors



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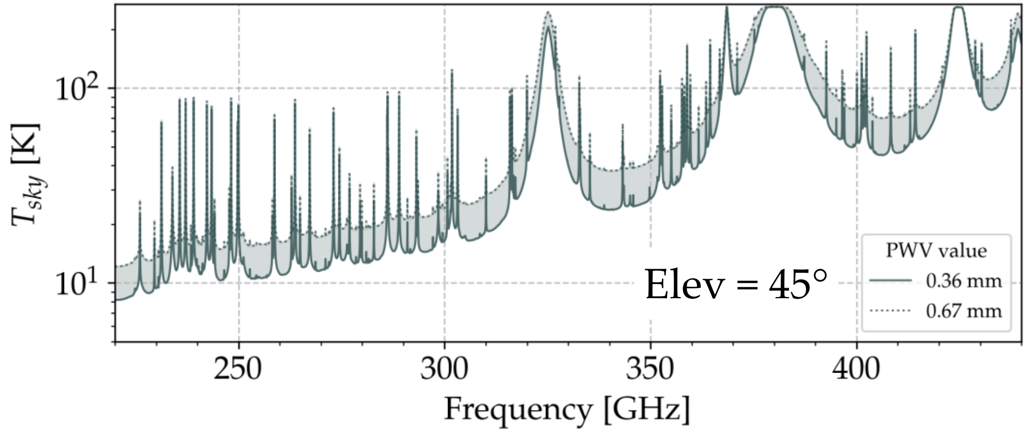
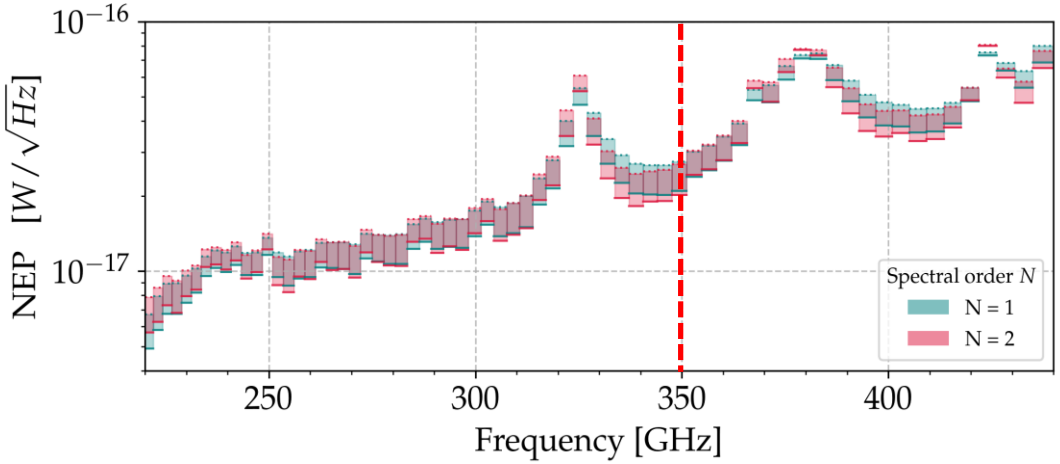


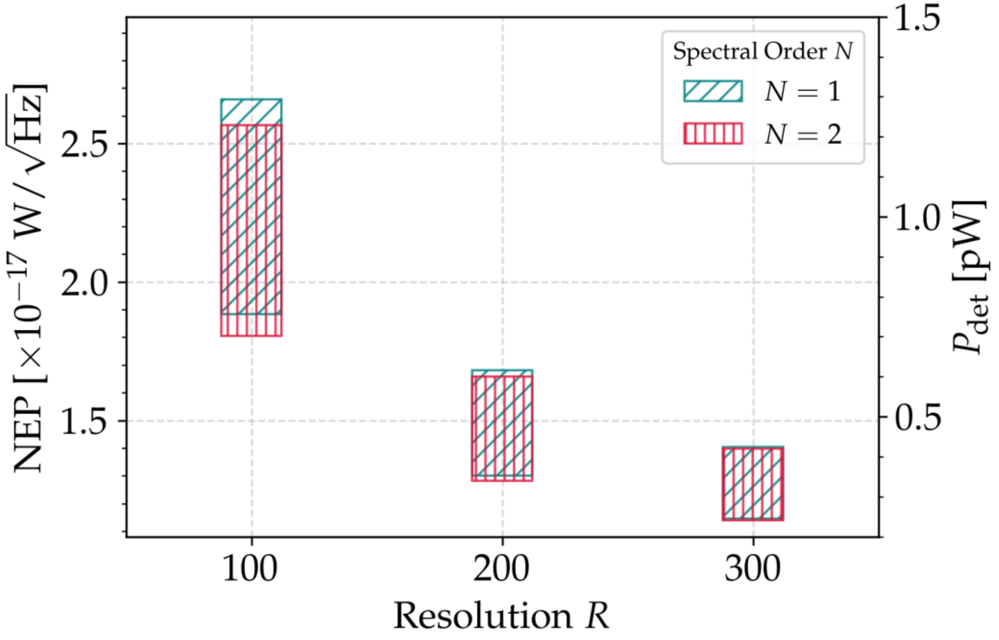
- Determines the NEP for photon-noise limited KIDs



Expected NEP of the channel detectors across the band for a $R = 100$ spectrometer

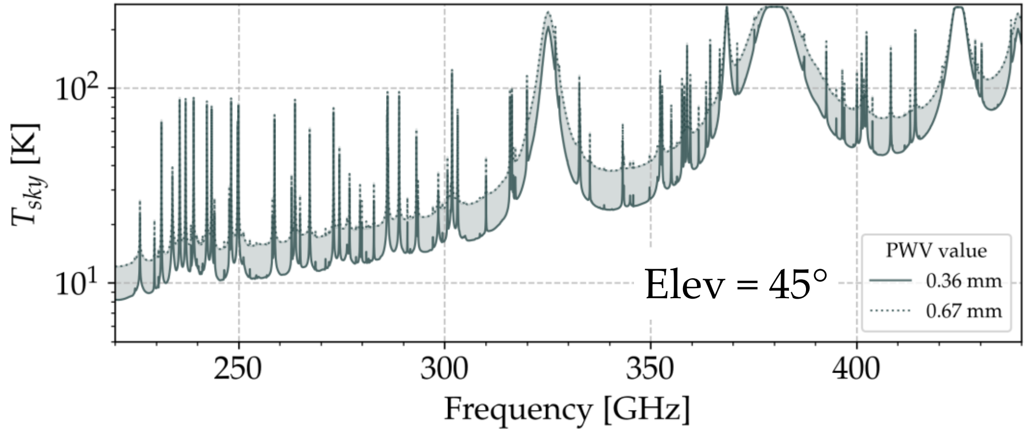
Detector considerations

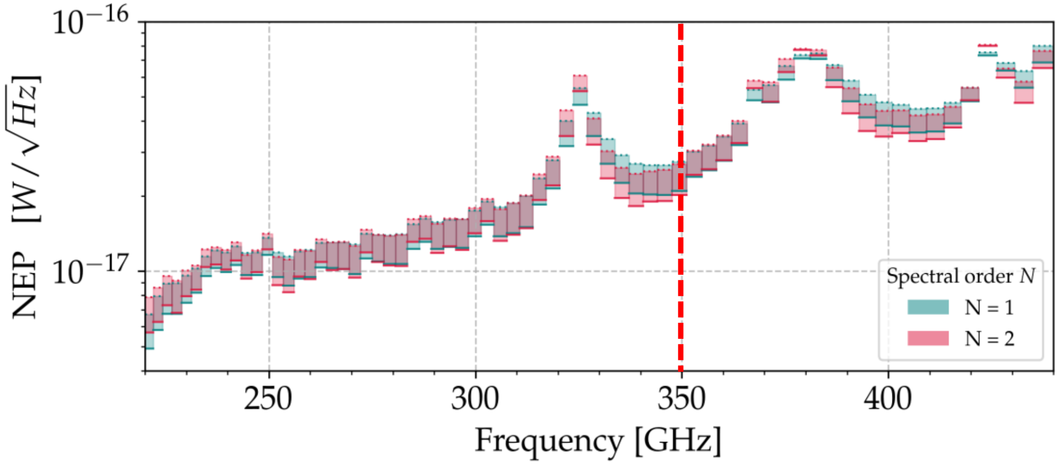
Implications on the detector performance?



- For a given R, NEP stays comparable
- Scales approx. NEP $\propto 1/\sqrt{R}$

Dynamic Range?





Expected NEP of the channel detectors across the band for a $R = 100$ spectrometer

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Can we develop this Spectrometer in-house?

Considerations

What should be the Spectrometer profile?

- Can we realise different spectral profiles? ✓
- Implication on spectrometer efficiency?
- What Resolution?

What is the expected Spectrometer performance?

- Influence on the [CII] signal recovery?
- Specifications on the detector noise?

Can we develop this Spectrometer in-house?

- Precise and compact design → *More voxel density in a large array*
- On Silicon-on-Insulator (SOI) membranes → *Low-loss and Low-noise*

→ *Actively developed (stay tuned!)*

Conclusions

- Filterbank spectrometers offer a new possibility for a next-generation LIM survey array instrument
  - Can be designed for broadband instrument
  - Allows for different spectral profiles
  - Integrated and compact structure, thus suitable for a large array

- A higher order spectral profile results in -
  - Higher spectrometer efficiency and better sensitivity
  - Improved [CII] signal recovery due to lower CO spillover
  - But detector noise performance is nearly independent

→ Expected faster mapping speeds with a whole Array instrument!

Thank you for your attention.